Chapter 2
A Soft-Switching Control Method of Isolated LC Series Resonant Transformer Full Bridge DC–DC Converter

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Abstract For the different characteristics of nonresonant and resonant isolated bidirectional full bridge DC–DC converter, a unified expression of power transmissions is derived from two DC–DC converters. The power transfer characteristics could be unified described through the power expression. The problem of isolated bidirectional DC–DC converter is that the switching loss increases and the converter efficiency declines with the forced turn-on or turn-off of switch devices in high-frequency situation. In this paper, to solve this problem, an isolated LC series resonant transformer full bridge DC–DC converter is taken as research object, a phase-shift control strategy which could realize zero voltage turn-on and decrease the turn-off current of the power devices to decrease switching loss and increase the efficiency is proposed. The validity of proposed control strategy is verified through simulation and experiment results.

Keywords Bidirectional full bridge DC–DC converter · Series resonant · Soft-switching technology · First harmonic analysis · Voltage gain

2.1 Introduction

The isolated bidirectional full bridge DC/DC converter, known as Dual Active Bridge (DAB), has the advantages that medium (or high) frequency transformer could realize electrical isolation, which improves system reliability, and soft
switch control of both primary side and secondary side of transformer that could reduce system loss. Bidirectional energy flow of converter could be achieved. High frequency transformer is used to replace the power frequency transformer, which could reduce the size and mass and improve power density of the system. Such converters are widely used in applications like power electronic transformer [1], locomotive traction [2], renewable energy power generation [3], high voltage motor drive [4, 5].

DC–DC converter, which is an important unit of power electronic transformer is utilized to achieve electrical isolation and voltage level conversion. According to the different topologies, it could be divided into nonresonant and resonant DC–DC converters. According the different control strategies, it could be divided into phase-shift control and combination of phase-shift and PWM modulation [6–12].

The main work in this paper is listed as:

(1) The unified power transfer expression, which could describe the relationship of resonant and nonresonant DC–DC converter, is derived in this paper. The derived expression helps in modeling and Analysis of DC–DC converter.

(2) Through the comparison and analysis of nonresonant and resonant DC–DC converter, a control strategy based on phase-shift control for resonant DC–DC converter is proposed in this paper.

2.2 The Principle of DC/DC Converter

Figure 2.1 shows the topology of an isolated LC series resonant transformer full bridge DC/DC converter. It consists of two active full bridges, a series resonance unit and an isolation transformer. \( L_r \) is the equivalent of primary and secondary leakage inductance of high frequency transformer. \( U_{ab} \) and \( U_{cd} \) are 50 % duty cycle square waves. \( \phi \) is the phase-shift angle of \( U_{ab} \) and \( U_{cd} \).

Considering the affection of line impedance of LC series resonance circuit and magnetic inductance of transformer, the approximate equivalent circuit and its phasor diagram of DC–DC converter is shown in Figs. 2.2 and 2.3.

where \( \theta, \beta, \phi \) are respectively phase differences among current \( i_r \), voltage \( U_{ab}, U_{cd} \). \( u'_{ab,f} \) and \( u'_{cd,f} \) are respectively the fundamental component of voltage \( U_{ab} \) and \( U_{cd} \). \( Z_{eq} \) is the equivalent impedance of \( R_o \) in the equivalent circuit.

Set \( \omega_r, \omega_s \) are resonant angular frequency and switching frequency, \( f_r, f_s \) are resonant frequency and switching frequency, \( n \) is turns ratio of transformer.

The fundamental of \( u_{ab} \) and \( u_{cd} \), which are defined as \( u_{ab,f} \) and \( u_{cd,f} \), could be expressed as follows:

\[
\begin{align*}
  u_{ab,f}(t) &= \frac{4}{\pi} U_i \cos \omega_s t \\
  u_{cd,f}(t) &= \frac{4}{\pi} U_o \cos(\omega_s t - \phi)
\end{align*}
\] (2.1)

(2.2)
In the approximate equivalent circuit, \( u_{cd} \) could be expressed as

\[
u_{0cd} f (t) = \frac{4}{\pi} U_0 o \cos \left( \frac{x_{st}}{C_0} / \right) \left( 90^\circ + \alpha \right) / C_0 U_0 o \left( x_{st} / C_0 / / C_0 90^\circ + \alpha \right) \frac{2}{C_0}.
\]

The Impedance of \( R, L_r \) and \( C_r \) in the LRC resonant circuit could be derived as

\[
Z = R + j \left( \omega_s L_r - \frac{1}{\omega_s C_r} \right) = |Z| \angle (90^\circ - \alpha)
\]

\[
|Z| = \sqrt{R^2 + \left( \omega_s L_r - \frac{1}{\omega_s C_r} \right)^2}
\]

So

\[
I_r = \frac{\dot{U}_{ab} f - \dot{U'}_{cd} f}{Z} = \frac{2\sqrt{2}}{\pi |Z|} \left( U_i \angle (\omega_s t - 90^\circ + \alpha) - U'_o \angle (\omega_s t - \phi - 90^\circ + \alpha) \right)
\]

The output instantaneous power \( p_o \), which is transferred through the secondary of transformer, could be derived as

\[
p_o = u_{cd} f(t) i_r(t) = \frac{16nU_o}{\pi^2 \sqrt{R^2 + (\omega_s L_r - \frac{1}{\omega_s C_r})^2}}.
\]
\[
\left\{ \frac{1}{2} U_i \left[ - \sin(2\omega t + \phi) + \sin(\phi + x) \right] - \frac{1}{2} U'_o \left[ - \sin(2\omega t + x - 2\phi) + \sin x \right] \right\}
\]

(2.7)

Considering \( U'_o = nU_o \), in the \( 0 \sim T \) period, the average power \( P_o \) of DC–DC converter could be re-expressed as

\[
P_o = \frac{8nU_o[U_i \sin(\phi + x) - nU_o \sin x]}{\pi^2 \sqrt{R^2 + \left( \frac{\omega s L_r - \frac{1}{\omega_s C_s}}{R_0^2} \right)^2}}
\]

(2.8)

Set \( F = \frac{\omega_o}{\omega_s}, \frac{Q}{Q_o} = \frac{\omega_s L_r}{R_0^2}, \) so \( \frac{\omega_s L_r}{R_0^2} = QF, \frac{1}{\omega_s C_s R_0} = \frac{Q}{F} \).

The average output power \( P_o \) is derived as

\[
P_o = \frac{8n \cdot U_o \cdot [U_i \cdot \sin(\phi + x) - nU_o \sin x]}{\pi^2 \sqrt{R^2 + (w_s L_r)^2 \cdot (F - 1/F)^2}}
\]

(2.9)

Formula (2.9) indicates that the average transfer power of DC/DC converter is determined by phase-shift \( \phi \) and output voltage \( U_o \).

### 2.3 Traditional Control Method of DC–DC Converter and Existing Problem

Traditional topology of DC–DC converter is shown in Fig. 2.4, where \( R \) is the circuit impedance, \( L \) is the leakage inductance of high frequency isolated transformer.

From formula (2.9), in nonresonant situation, the converter output power \( P_o \) is re-expressed as

\[
P_o = \frac{8n \cdot U_o \cdot U_i}{\pi^2 \cdot w_s \cdot L_s} \sin \phi
\]

(2.10)

Under PWM modulation, the typical waveforms of voltage \( U_{ab} \) and current \( i_i \) is shown in Fig. 2.5.

From Fig. 2.5, the turn-off current is very high in hard-switching mode. The forced shut-off mode of switching devices is called hard-switching. The circuit structure is simple, however, the switching loss is greater.

### 2.4 Improved Control Method of DC–DC Converter

To decrease the switching loss and improve converter efficiency, in this paper, an isolated LC series resonant transformer full bridge DC/DC converter, which is
shown in Fig. 2.1, is taken into research. Two power transmission modes are given based on analysis of formula (2.9).

### 2.4.1 Synchronous Control Mode

If \( F = 1, \phi = 0 \), formula (2.9) is expressed as

\[
P_o = \frac{8n \cdot U_o}{\pi^2 \cdot R} \left( U_i - n \cdot U_o \right) \tag{2.11}
\]

From the output load power:

\[
P_{\text{load}} = \frac{U_o^2}{R_o} \tag{2.12}
\]

From formula (2.11) and (2.12), the transmission power could be re-expressed as

\[
P_o = \frac{8n \cdot U_i \cdot R_o}{8n^2 R_o + \pi^2 R} \tag{2.13}
\]

Formula (2.13) indicates that power transmission is determined by differential of input and output voltage in synchronous mode. The output voltage \( U_o \) is determined by load \( R_o \). Assuming the turn ratio of transformer is 1, the typical waveforms of voltage \( U_{ab} \) and current \( i_r \) is shown in Fig. 2.6.
Figure 2.6 indicates that it is a synchronization action for switching devices of both primary and secondary sides under such power transmission mode. The output voltage $U_o$ is determined by load $R_o$. This method is suitable for the situation that the variation range of $U_o$ is not great.

### 2.4.2 Phase-Shift Control Method

If $F \neq 1$, $\phi \neq 0$, neglecting circuit impedance, $\alpha = 0$, the average transmission power $P_o$ could be described as

$$P_o = \frac{8n \cdot U_o \cdot U_i}{\pi^2 \cdot \left(w_sL - \frac{1}{w_cC_s}\right)} \quad (2.14)$$

Via adjusting phase-shift $\phi$, the output power $P_o$ and output voltage $U_o$ could be closed-loop controlled. Assuming the turn ratio of transformer is 1, the typical waveforms of voltage $U_{ab}$ and current $i_r$ is shown in Fig. 2.7.

The voltage gain of the equivalent circuit, namely the ratio of output voltage and input voltage could be defined as

$$M = \left|\frac{U_{cd,f}}{U_{ab,f}}\right| \quad (2.15)$$

Figure 2.7 shows that when $\omega_s t = 0$, $i_r(0) < 0$, namely $\sin(-\beta) < 0$, the primary side achieved ZVS and when $\omega_s t = \phi$, $i_r(t_1) > 0$, namely $\sin(-\theta) < 0$, the secondary side achieved ZVS. So constraint equations of soft switch could be derived as follows:
If only $M = 1$, the equations could be satisfied. In this mode, the realization of soft-switching is independent of the load. It means that ZVS of primary side and secondary side could be achieved over a wide load range.

### 2.5 Simulation and Experiment

#### 2.5.1 Simulation

From the above theoretical analysis, PSIM is utilized to verify the proposed strategy. The simulation parameters are list as the following.

In nonresonant situation, $L$ is 30 μH, switching frequency $f_s$ is 6 kHz, load $R_o$ is 7 Ω. The input voltage $U_i$ is, respectively, set to 50 V and 100 V, (corresponding output power 0.36 kW and 1.43 kW), the waveforms of driving signal, $U_{ab}$, $U_{cd}$ and $i_r$ are shown in Figs. 2.8 and 2.9.

In resonant situation, the resonant inductor $L_r$ is 30 μH, resonant capacitor $C_r$ is 20 μF, resonant frequency $f_r$ is 5.3 kHz, switching frequency $f_s$ is 6 kHz, load $R_o$ is 7 Ω. When input voltage $U_i$ is, respectively, set to 50 and 100 V, (corresponding output power is 0.36 and 1.43 kW), the waveforms of driving signal, $U_{ab}$, $U_{cd}$ and $i_r$ are shown in Figs. 2.10 and 2.11.
Fig. 2.8 Waveforms of $U_{ab}$, $U_{cd}$ and $i_r$ when $U_i = 50$ V

Fig. 2.9 Waveforms of $U_{ab}$, $U_{cd}$ and $i_r$ when $U_i = 100$ V

Fig. 2.10 Waveforms of $U_{ab}$, $U_{cd}$ and $i_r$ when $U_i = 50$ V

Fig. 2.11 Waveforms of $U_{ab}$, $U_{cd}$ and $i_r$ when $U_i = 100$ V

Fig. 2.12 Waveforms of $U_{ab}$, $U_{cd}$ and $i_r$ when $U_i = 50$ V
2.5.2 Experiment

The parameters of actual circuit are as follows: transformer turns ratio \( r = 1 \), \( L_s = 30 \, \mu \text{H} \), \( P_s = 10 \, \text{kW} \), \( L_r = 15 \, \mu \text{H} \), \( C_r = 20 \, \mu \text{F} \), \( R_o = 7 \, \Omega \), \( f_s = 6 \, \text{kHz} \), \( f_r = 5.3 \, \text{kHz} \), \( t_{\text{dead}} = 2 \, \mu \text{s} \).

Where \( r \) is transformer ratio, \( P_s \) is rated power, \( t_{\text{dead}} \) is switching tube dead-time.

Figures 2.12 and 2.13 shows the waveforms of \( U_{\text{ab}} \), \( U_{\text{cd}} \) and \( i_r \) when input voltage is respectively 50 and 100 V.

In order to verify the efficiency of soft-switching of the system, experiment curves are depicted to calculate system efficiency in non-resonant mode and resonant mode. The output power are, respectively 0.36, 1.43, 3.21 and 5.71 kW. Comparison results are shown in Fig. 2.14.

Experiments results indicate that the efficiency is higher under resonant mode.
2.6 Conclusion

Based on the comparison of power transfer mode and control features for non-resonant and LC resonant DC–DC converter, the conclusion is:

1. The proposed power transfer unified expression could describe the power transmission characteristics of nonresonant and resonant DC–DC converter in one formula. This expression is helpful for analysis and modeling of DC–DC converter.

2. Under phase-shift control method for resonant mode of DC–DC converter, the turn-off current could be decreased, and the efficiency could be improved.

References

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